Six-Week Gait Retraining Program Reduces Knee Adduction Moment, Reduces Pain, and Improves Function for Individuals with Medial Compartment Knee Osteoarthritis

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ABSTRACT: This study examined the influence of a 6-week gait retraining program on the knee adduction moment (KAM) and knee pain and function. Ten subjects with medial compartment knee osteoarthritis and self-reported knee pain participated in weekly gait retraining sessions over 6 weeks. Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores and a 10-point visual-analog pain scale score were measured at baseline, post-training (end of 6 weeks), and 1 month after training ended. Gait retraining reduced the first peak KAM by 20% ($p < 0.01$) post-training as a result of a 7° decrease in foot progression angle (i.e., increased internal foot rotation), compared to baseline ($p < 0.01$). WOMAC pain and function scores were improved at post-training by 29% and 32%, respectively ($p < 0.05$) and visual-analog pain scale scores improved by two points ($p < 0.05$). Changes in WOMAC pain and function were approximately 75% larger than the expected placebo effect ($p < 0.05$). Changes in KAM, foot progression angle, WOMAC pain and function, and visual-analog pain score were retained 1 month after the end of the 6-week training period ($p < 0.05$). These results show that a 6-week gait retraining program can reduce the KAM and improve symptoms for individuals with medial compartment knee osteoarthritis and knee pain. J Orthop Res 31:1020–1025, 2013.

Keywords: gait modification; real-time feedback; symptomatic; WOMAC; visual-analog

Knee osteoarthritis (OA), which affects roughly one in five adults over age 45,[1] can be painful and decrease quality of life.[2] The medial compartment is affected 10 times more often than the lateral compartment,[3] which is likely due to greater medial compartment loading during gait.[4] The first peak of the external knee adduction moment (KAM) is often used as a surrogate measure of medial compartment loading[5,6] and has been correlated with pain[7] and the presence,[8] severity,[9] and progression[10] of medial compartment knee OA. Thus, conservative treatments that reduce the KAM hold potential for treating symptoms and slowing OA progression.

Gait modification is a non-surgical treatment that can reduce the KAM. Changes to foot progression angle,[11,12] tibia angle,[13] hip adduction/internal rotation,[14] and trunk sway[13,15,16] can reduce the KAM from baseline. Modifications involving simultaneous changes to multiple gait parameters have also been shown to reduce the KAM.[13,17,18]

Although it is clear that gait modification can reduce the KAM, the potential benefits of gait retraining for individuals with knee OA and knee pain are unclear. Most gait retraining studies have examined either healthy subjects or pain-free knee OA patients (see review article[19]); thus, it is unknown whether gait retraining to reduce the KAM improves knee pain and function in subjects with knee OA and knee pain. Additionally, while Barrios et al.[14] conducted gait retraining trials on healthy subjects over multiple sessions, the vast majority of gait retraining studies have been performed during a single session without further follow-up (see review article[19]); thus the persistence of the gait modifications and the effect on knee pain and function over time from these studies is unknown. To assess whether gait retraining is a viable treatment for individuals with knee OA and knee pain, it would be valuable to know whether gait can be modified to reduce the KAM and pain in these subjects and if the gait modifications are retained after training has concluded.

The purpose of this study was to evaluate the effect of a 6-week gait retraining program on the first peak KAM and knee symptoms for individuals with medial-compartment knee OA and self-reported knee pain. We hypothesized that 6 weeks of gait retraining would (1) reduce the first peak knee adduction moment and (2) improve knee pain and function as measured by the Western Ontario and McMaster Universities (WOMAC) score[20] and a visual-analog pain scale.[21] We further hypothesized that (3) the changes induced by gait retraining would be retained 1 month after the end of the 6-week training period.

METHODS

Subjects

Ten subjects (Table 1) participated after giving informed consent in accordance with Stanford University's Institutional Review Board. To be included, subjects were required to have radiographic evidence of medial compartment knee OA (Kellgren & Lawrance [K/L] Grade > 1) and to have self-reported medial compartment knee pain at least 1 day per week during each of the 6 weeks prior to participation.

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Table 1. Demographics of Subjects With Medial Compartment Knee Osteoarthritis and Self-Reported Knee Pain

Characteristics	Mean (SD)
Age (yr)	60 (13)
Height (cm)	171 (9)
Mass (kg)	79 (20)
BMI (kg/m^2)	26.6 (4.7)
Gender	F: 4, M: 6
Kellgren & Lawrence grade	II: 3, III: 6, IV: 1

Subjects were also required to be between 18 and 80 years and to be able to walk unaided for at least 25 consecutive minutes. Exclusion criteria included: body mass index greater than 35; inability to adopt an altered gait due to previous injury or surgery on the back or lower extremities; use of a shoe insert or hinged knee brace; or corticosteroid injection within the previous 6 weeks. Gait retraining and analysis was focused on the leg with greatest self-reported knee pain (four right legs, six left legs).

Subjects came to the laboratory a total of eight times. The first session was to determine baseline pain and function, identify baseline walking patterns, identify an individualized altered gait pattern for each subject, and to train the subject to walk with this new altered gait. The following six sessions were spaced 1 week apart and were used as gait retraining sessions, with the last of these sessions defined as the end of the gait retraining (i.e., the post-training session). Subjects returned to the laboratory for a follow-up session 1 month after the post-training session. During the post-training session and at the 1 month follow-up, walking kinematics, knee loading, pain, and function were re-assessed.

Gait Retraining Sessions

At the beginning of each testing session, a static standing calibration trial was performed with markers placed at the following locations: calcaneous, head of second metatarsal, head of the fifth metatarsal, lateral and medial malleoli, lateral and medial femoral epicondyles, lateral mid-shaft shank (two markers), greater trochanter, lateral mid-shaft femur (two markers), left and right anterior superior iliac spines, left and right posterior superior iliac spines, left and right acromion, and seventh cervical vertebrae. Medial malleolus and medial epicondyle markers were removed for subsequent walking trials. Marker trajectories were recorded with an eight-camera motion capture system (Vicon, Oxford Metrics Group, Oxford, UK) at 60 Hz, and treadmill forces and moments were recorded at 1,200 Hz.

Subjects performed all walking trials on a split belt instrumented treadmill (Bertec Corporation; Columbus, OH). During the first session only, subjects began by walking for 2 min to warm up and establish a preferred treadmill walking speed (average $= 1.22 \pm 0.21$ m/s). Following the warm up, subjects were instructed to walk normally for another two minutes. The last 10 steps of this trial were averaged to establish the following baseline parameters: external knee adduction moment (KAM), external knee flexion moment, foot progression angle, and trunk sway angle (definitions below in Data Analysis Section). The altered gait pattern was determined based on a minimized combined kinematic change from the foot progression angle and trunk sway angle which reduced the first peak KAM by at least 10%. A least squares fit between kinematic parameters and KAM values for a series of single gait parameter change and multi-gait parameter change trials was used to create a linear model. The model was used to project necessary kinematic changes to attain at least a 10% reduction in the KAM (see Shull et al.[13] Section "Data-driven gait retraining" and Shull et al.[22] Section "Computation: Localized Linearization Modeling to Predict New Gaits" for details). After the altered gait pattern was identified, subjects were encouraged to walk with both altered kinematic parameters but were given the freedom to choose to walk with only an altered foot progression angle or only an altered trunk sway angle. Subjects who choose to walk with only one kinematic change were asked why only one parameter was chosen. After subjects learned the new gait pattern in the initial session (Week 0), all remaining sessions (Weeks 1–6 and 1 month follow-up) involved subjects walking with the altered gait pattern at their same preferred treadmill speed as determined in the initial session. Subjects wore their own walking shoes, which were the same for all sessions. Between gait retraining sessions, subjects were instructed to practice walking with the altered gait pattern on their own outside of the laboratory during which time they received no feedback. They were instructed to practice at least 10 min per day and were given weekly activity logs to record the time of day and amount practiced each day during the 6 weeks of gait retraining. Practice logs were submitted weekly.

Gait retraining was accomplished through real-time sensing and feedback, which has previously been shown effective in retraining walking kinematics.[13,14,16,18] Marker trajectories, ground reaction forces and moments were streamed via TCP/IP to an xPC computer for real-time computation using Matlab (Mathworks, Natick, MA). Real-time haptic (touch) feedback was used to instruct changes to foot progression angle and trunk sway angle via vibration motors (Engineering Acoustics, Inc., Casselberry, FL). Hypoallergenic double-sided tape was used to adhere the motors to the skin. One vibration motor was placed on the lateral–proximal aspect of the fibula and vibrated once to indicate a required decrease in foot progression angle (toe-in more) and twice to indicate a required increase in foot progression angle (toe-out more). Because foot progression angle and tibia angle are correlated,[22] and because it is easier for subjects to sense vibrations from a motor placed on the shank than from one placed on the shoes,[23] real-time feedback was computed based on tibia angle. Thus, tibia angle was a surrogate measure for training foot progression angle. Three vibration motors were placed on the upper back. One motor was placed at the center of each of the left and right scapula and one at the second thoracic vertebrae. Alternating vibrations from the two scapula motors indicated a required increase in trunk sway and a vibration from the motor on the spine indicated a required decrease in trunk sway. Vibration configuration and feedback methodology were based on previous comparisons of haptic feedback strategies for training kinematic gait changes.[24] Feedback was given on each step. No vibration feedback indicated the gait parameter needed no correction during the current step.

The amount of haptic feedback during each session decreased from week-to-week (Fig. 1), in a similar manner as the previously described fading feedback design.[14,25] This was done so that subjects would not solely rely on the feedback and would internalize the altered gait pattern.[26] At

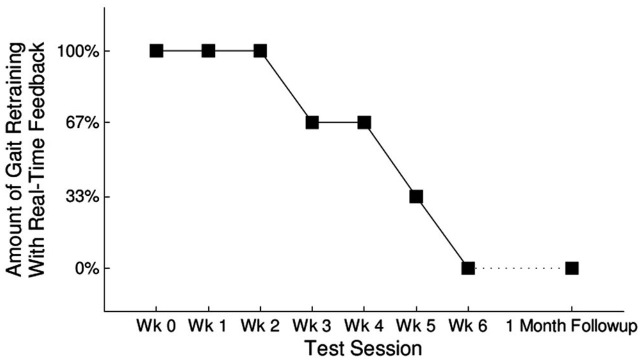

Figure 1. Percentage of real-time feedback given during each testing session. The amount of feedback decreased across sessions in a similar manner as the previously described fading feedback design.[14,25] Sessions were spaced 1 week apart, and there was 1 month between the post-training session (Week 6) and 1 month follow-up [Wk: Week].

post-training (Week 6) and the 1 month follow-up session, no haptic feedback was given. Instead, subjects performed a 2-min trial, walking with the altered gait pattern they had been practicing since the first session without verbal prompting on how to walk. As in the baseline trial during Week 0, the last 10 steps were averaged to determine the KAM, knee flexion moment, foot progression angle, and trunk sway angle (definitions below in Data Analysis Section).

Knee Pain and Function Measures

The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC)[20] questionnaire was used to assess knee pain and function, and a visual-analog pain scale[21] was used as an additional measure of knee pain. Subjects completed the WOMAC and visual-analog pain scale at the beginning of the session prior to testing at baseline, post-training, and 1 month follow-up. WOMAC pain and function subscales were transformed to a 100-point scale, with 100 representing full function and no pain. The visual-analog pain scale ranged from 0 "no hurt" to 10 "hurts worst."[21]

Data Analysis

Marker data were low-pass filtered at 6 Hz and force plate data at 50 Hz using a zero-lag fourth-order, Butterworth filter. The line of forward progression was aligned with the long axis of the treadmill. The laboratory vertical axis was perpendicular to the treadmill surface. Foot progression angle was defined in the laboratory horizontal plane as the angle between the line connecting the calcaneous and second metatarsal head and the line of forward progression. Toe-out was considered positive. Tibia angle was defined in the laboratory frontal plane as the angle between the line connecting the lateral malleolus and lateral femoral epicondyle and the line of the laboratory vertical axis. Tibia angles lateral of vertical were considered positive. Trunk sway angle was defined in the laboratory frontal plane as the angle between the line connecting the seventh cervical vertebrae and the midpoint between left and right posterior superior iliac spines and the line of the laboratory vertical axis. Trunk sway lateral of vertical in the direction of the training leg was considered positive. The external knee adduction and knee flexion moments were reported in the tibial reference frame and were scaled by subject height times body weight. KAM, foot progression angle, and trunk sway angle were analyzed at the first peak of the KAM. Knee flexion moment was reported as the overall peak during stance.

Repeated measures, one-way analysis of variance (ANOVA) was used to detect a difference among measurements taken at baseline, post-training, and 1 month follow-up; Tukey's method was used for post hoc pairwise comparison ($\alpha = 0.05$). WOMAC pain and function effect sizes were calculated as the mean difference divided by the standard deviation between baseline and post-training. Effect sizes were compared with expected placebo effect size 95% confidence intervals for osteoarthritis treatments based on a review article which compiled the placebo effect on WOMAC pain in 180 studies and WOMAC function in 80 studies.[27] Repeated measures ANOVA was used to compare reported practice time from activity logs between weeks and between days of the week ($\alpha = 0.05$).

RESULTS

Six weeks of gait retraining resulted in an average 20% reduction in the first peak KAM ($p < 0.01$), post-training compared to baseline (Fig. 2, Table 2). There was no change in the second peak KAM ($p = 0.07$). Foot progression angle decreased (i.e., increased internal foot rotation) post-training by an average of 7° ($p < 0.01$) while trunk sway angle was unchanged ($p = 0.54$; Table 2). All subjects chose not to modify trunk sway (average of 1° desired increase based on minimized kinematic change[13]), but instead chose to modify foot progression angle. All subjects reported at least one of the following reasons for choosing not to modify trunk sway: (1) felt uncomfortable, (2) difficult to maintain, and/or (3) decreased balance.

At the 1 month follow-up session, subjects continued to walk with a reduced KAM and foot progression angle, compared to baseline (Table 2; $p < 0.05$). There was no change in the second peak KAM at 1 month follow-up ($p = 0.77$). There was no change in peak

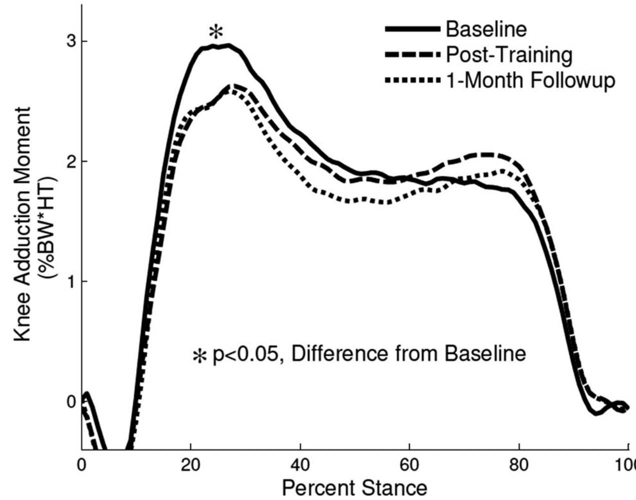

Figure 2. Average knee adduction moment for all subjects. * denotes significant difference from baseline ($p < 0.05$). The first peak knee adduction moment significantly decreased during post-training and 1 month follow-up compared to baseline, while there were no differences in the second peak knee adduction moment.

Table 2. Average Gait Mechanics at Baseline, Post-Training, and 1 Month Follow-Up

	Baseline	Post-Training	1 Month Follow-Up
Knee adduction moment (%BW × HT)	3.11 (1.40)	2.61 (1.47)*	2.67 (1.41)*
Foot progression angle (deg)	2.1 (4.0)	−5.1 (5.1)*	−6.0 (4.7)*
Trunk sway angle (deg)	1.0 (2.1)	0.7 (1.6)	0.7 (1.5)
Knee flexion moment (%BW × HT)	1.95 (0.76)	1.67 (0.75)	1.43 (0.70)

Standard deviation values reported in parentheses. Knee adduction moment, foot progression angle, and trunk sway angle were reported at the first peak knee adduction moment and knee flexion moments were measured at the overall peak knee flexion moment during stance. *Denotes significant difference from baseline ($p < 0.05$). There were no significant differences between post-training and 1 month follow-up.

knee flexion moment between baseline and post-training ($p = 0.35$) or 1 month follow-up ($p = 0.08$; Table 2).

Six weeks of gait retraining resulted in a 29% improvement in WOMAC pain ($p < 0.05$), and a 32% improvement in WOMAC function ($p < 0.05$), post-training compared to baseline (Fig. 3). An improvement in knee pain symptoms was also evident in a two-point reduction in visual-analog pain scale score ($p < 0.05$), post-training compared to baseline (Fig. 4). WOMAC pain and function effect sizes were approximately 75% higher ($p < 0.05$) than the expected osteoarthritis treatment placebo (Fig. 5). At the 1 month follow-up session, subjects continued to demonstrate improvements in WOMAC pain and function (Fig. 3) and visual-analog pain score (Fig. 4) compared to baseline ($p < 0.05$).

Subjects completed 97% of weekly activity logs and reported practicing the altered gait an average of 33 ± 26 min/day. There were no significant differences in reported practice times between weeks ($p = 0.80$) or between days of the week ($p = 0.78$).

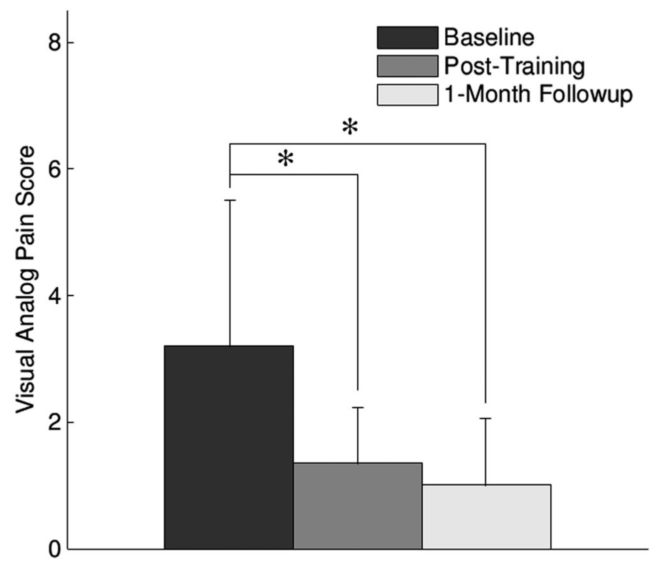

Figure 4. Mean with one standard deviation bars for visual-analog pain scale score at baseline, post-training, and 1 month follow-up. The visual-analog pain scale ranged from 0 "no hurt" to 10 "hurts worst."[21] *Denotes significant difference from baseline ($p < 0.05$).

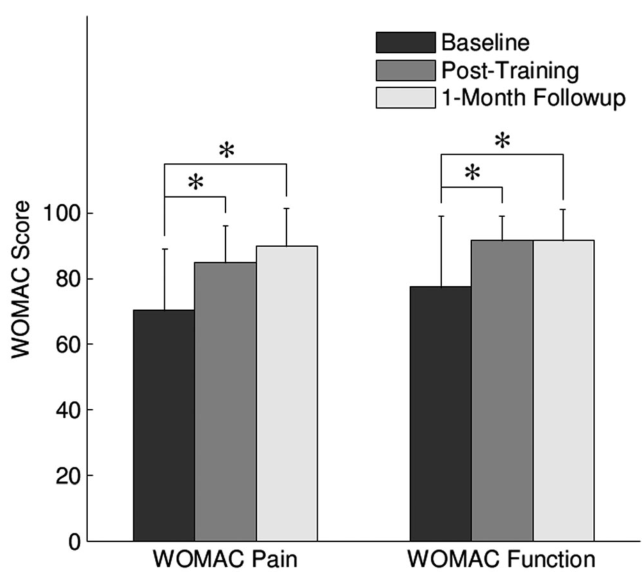

Figure 3. Mean with one standard deviation bars for Western Ontario and McMaster Universities Osteoarthritis Index[20] (WOMAC) pain and function score at baseline, post-training, and 1 month follow-up. *Denotes significant difference from baseline ($p < 0.05$). Note, an increase in WOMAC pain score indicates reduced pain.

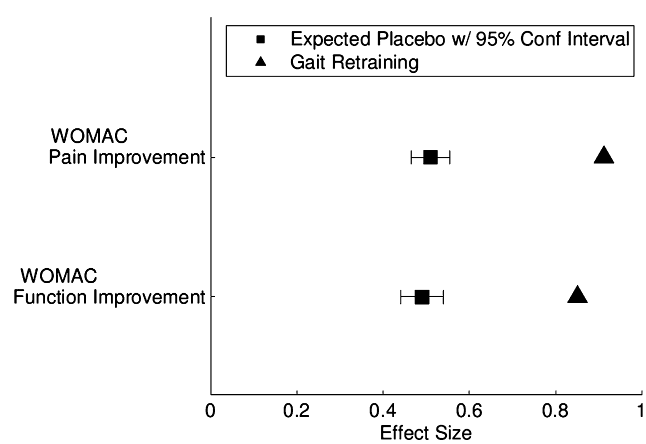

Figure 5. Comparison of effect size (mean difference divided by standard deviation between baseline and post-training) between gait retraining and the expected placebo effect with 95% confidence interval for Western Ontario and McMaster Universities Osteoarthritis Index[20] (WOMAC) pain and function score. Expected placebo and confidence intervals were computed from the placebo effect for osteoarthritis treatments from 180 WOMAC pain studies and 80 WOMAC function studies.[27]

DISCUSSION

This study investigated knee loading and pain and function changes following a 6-week gait retraining program for individuals with medial compartment knee OA and self-reported knee pain. In support of our first hypothesis, the first peak KAM was reduced post-training compared with baseline. In support of the second hypothesis, WOMAC pain and function scores improved and the visual-analog pain scale score decreased post-training compared to baseline. In support of the final hypothesis, the changes induced by gait retraining were retained 1 month after the end of the 6-week training period.

The 20% reduction in KAM achieved post-training (Table 2) is clinically relevant. The risk of progression of medial compartment knee OA is sensitive to changes in the KAM.[10] The 20% reduction in the KAM shows promise for slowing OA progression and is greater than other non-surgical interventions such as lateral wedge insoles (9% reduction),[28] valgus knee braces (6% reduction),[29] and variable stiffness shoes (6% reduction).[30] Surgical interventions such as high tibial osteotomy can provide a greater reduction in the KAM (33% reduction).[31] The reduced KAM occurred without an associated increase in knee flexion moment (Table 2). This is important because an increased peak external knee flexion moment can eliminate the potential medial compartment force reduction from the decrease in the KAM.[32]

The gait retraining program conducted in this study reduced knee pain and improved function (Fig. 3). Though gait retraining has been shown to reduce the KAM and it shows promise as a non-surgical treatment for knee OA, most gait retraining studies have enrolled healthy, asymptomatic subjects (see review article[19]), leaving the effect of gait retraining on patient symptoms unexplored. One study successfully performed a 6-week gait retraining protocol to reduce the KAM for healthy individuals who were at risk for developing medial compartment knee OA due to varus knee alignment.[14] Other studies have shown that individuals with knee OA can learn a modified gait pattern during a single training session,[11,12,17] though changes in symptoms were not reported. In the present study, subjects were not monitored on how closely they walked with the altered gait pattern while practicing on their own outside of the laboratory; they nevertheless saw significant benefits in reduced knee loading and improved symptoms. This suggests that is may be unnecessary to require laboratory gait retraining sessions more frequently than once per week or to closely monitor gait kinematics while subjects practice outside of the laboratory.

The pain and function improvements observed in the present study were about 75% larger than improvements from an expected placebo effect (Fig. 5).[27] The pain and function improvements were outside of the 95% confidence interval (Fig. 5), suggesting that symptom improvements likely resulted from the gait retraining intervention and not simply from a placebo effect. Clinically, the improvements in pain and function were above the minimal perceptible clinical improvement defined for OA patients using the WOMAC questionnaire.[33]

Toe-in gait has previously been shown to reduce the first peak KAM as the knee joint center shifts medially and the center of pressure shifts laterally.[11] Since the knee joint is slightly flexed during early stance, rotating the toes medially causes the knee joint center to shift medially, closer to the line of action of the ground reaction force, thereby reducing the lever arm of the KAM. At the same time, the heel rotates externally and the center of pressure shifts laterally moving the line of action of the ground reaction force closer to the knee joint center, which also reduces the lever arm of the KAM. Since subjects normally walk with toes pointed slightly outward and the toe-in modification was relative to baseline foot progression angle, toe-in gait in general made the foot progression angle appear straight and more aligned with forward progression (see Shull et al.[11]—Fig. 1) as opposed to "duck-footed" or "pigeon-toed."

All subjects found that increased trunk sway felt uncomfortable, was difficult to maintain, or decreased balance. Previous studies involving healthy subjects found that increasing trunk sway during ambulation can significantly reduce the KAM.[13,15,16] However, increased trunk sway tends to appear uncomfortable and unnatural (e.g., Mundermann[15]—Fig. 1; Shull[13]—Fig. 3; and Hunt[16]—Fig. 1). Qualitatively, we observed that it was more difficult for the knee OA subjects in this study to alter trunk sway compared to foot progression angle.

This study focused on individuals with knee OA and self-reported knee pain who were able to walk for 25 min without aid. Subjects generally reported muscle soreness in the first few weeks while learning to adopt the altered gait pattern, but the soreness typically disappeared by the third or fourth week. More severe OA subjects who cannot walk as far may be unable to learn an altered gait and may not be well-suited for this type of intervention. Long-term follow-up assessments were not performed beyond 1 month. At 1 month follow-up, subjects demonstrated learning retention and improved symptoms. However, it is unclear whether these results would remain 1, 2, or 5 years beyond the training period. Long-term follow-up could also detect potential radiographic changes resulting from altered gait patterns. Finally, this study did not contain a control group. Results from the test group were compared with an extensive set of studies on OA placebo,[27] giving confidence that symptom changes were likely not solely due to the placebo effect. Including a control group comprised of a similar population with knee OA and knee pain that followed the same protocol but for an unchanged gait that did not reduce the KAM would demonstrate this more conclusively.

In conclusion, this study demonstrated that gait retraining can reduce the KAM, reduce pain and improve function for subjects with medial compartment knee OA and self-reported knee pain. In addition, the subjects retained their gait adaptation at 1 month follow-up. These results demonstrate the potential for gait retraining, as a non-surgical intervention, to improve symptoms and slow osteoarthritis progression for individuals with medial compartment knee OA and knee pain.

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